Final results on $\mathrm{K}^+ \rightarrow \pi^+\nu\bar{\nu}$ from BNL E949

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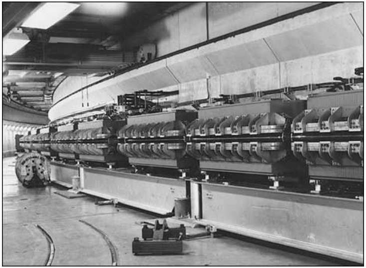


HIGH ENERGY PHYSICS

THE UNIVERSITY OF CHICAGO

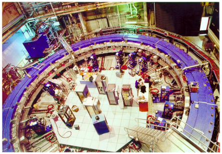
1. What is our quest?
2. How was it done?
3. What are the results?

Our quest

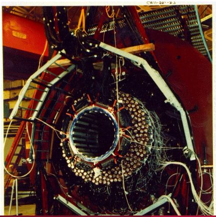
Where does the Standard Model of particle physics break down?
Two ways to look for "new physics":

Intensity frontier

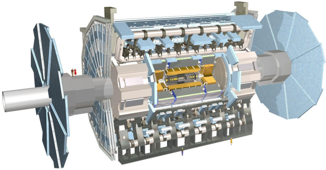
Precision measurements (muon g-2)



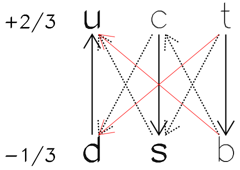
Rare decays ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)



Energy frontier (LHC)

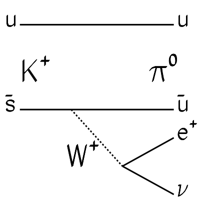


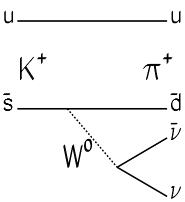
$K^+ \to \pi^+\nu\bar{\nu}$ probes the basic constituents of matter



Heavy quarks decay to lighter quarks via the weak interaction

In the early 1970's...





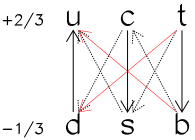
Observed (5%)

Not observed ($<10^{-6}$)

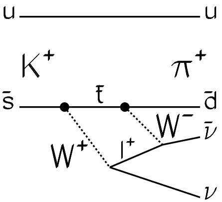
All observed flavor-changing decays also change electric charge

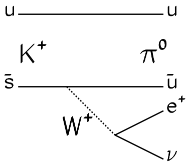
No evidence of flavor-changing neutral currents (FCNC) as predicted by theory of the time.

$K^+ \to \pi^+\nu\bar{\nu}$ probes the basic constituents of matter



Third generation with $m_t >> m_c, m_u$ permits $K^+ \to \pi^+\nu\bar{\nu}$ decay at second order.





Observed (5%)

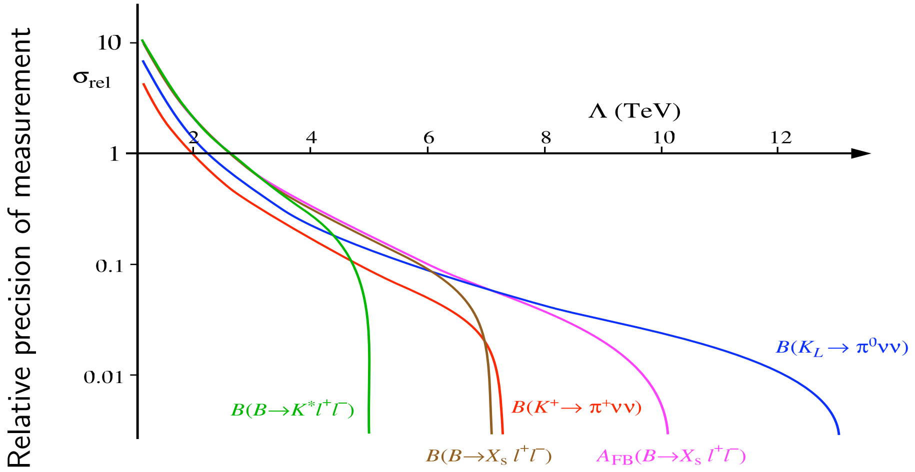
FCNC of $K^+ \to \pi^+\nu\bar{\nu}$ in SM

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \propto |V^*_{ts}V_{td}|^2$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$

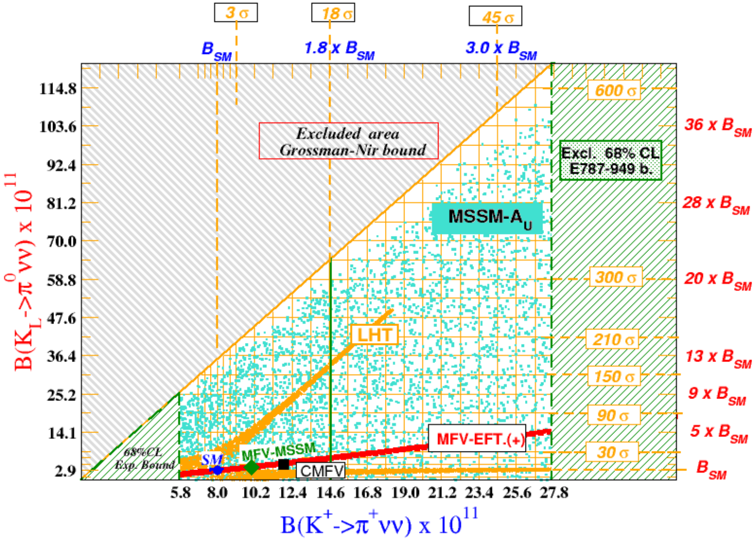
Strong interaction (QCD) part of $K^+ \to \pi^+\nu\bar{\nu}$ decay is related by isospin to $K^+ \to \pi^0 e^+\nu$ decay.

Sensitivity to New Physics



Ref: D.Bryman *et al.*, hep-ph/0505171. Assumes MFV.

Sensitivity to New Physics



Ref: G.Isidori, arXiv:0801.3039, attributed to Frederico Mescia

Experimental challenges of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$

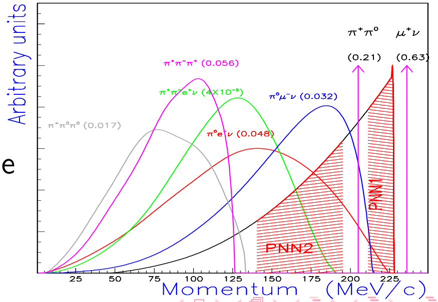
The decay $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ has a relatively weak experimental signature.

1. These is only one observable particle, the π^+, among the three particles in the final state because neutrinos interact too weakly to be observed.
2. The π^+ can be produced with a range of kinematically allowed values.
3. Only about 8 out of 100,000,000,000 K^+ are expected to decay to $\pi^+\nu\bar{\nu}$.

$K^+ \to \pi^+\nu\bar{\nu}$ can be observed. Previous BNL E787/E949 results.

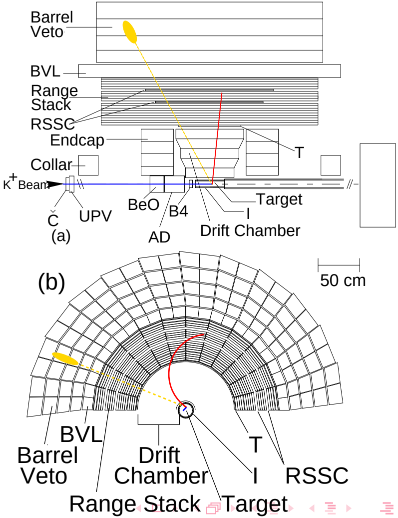
Region	**"PNN2"**	**"PNN1"**
$P(\pi^+)$ MeV/c	[140,195]	[211,229]
Stopped K^+	1.7×10^{12}	7.7×10^{12}
Background events	1.22 ± 0.24	0.45 ± 0.06
Candidate events	1	3
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$< 22 \times 10^{-10}$ (90% CL)	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$
Reference	PRD**70**, 037102 (2004)	PRD**77**, 052003 (2008)
	E787	E787& E949

Rate *vs.*
π^+ momentum in K^+ rest frame



E949 experimental method

- **Measure everything possible**
- $\sim 700\ \mathrm{MeV}/c\ \mathrm{K}^+$ beam
- Stop K^+ in scint. fiber target
- Wait at least 2 ns for K^+ decay
- Measure π^+ momentum P in drift chamber
- Measure π^+ range R and energy E in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in RS
- Veto photons, extra charged tracks



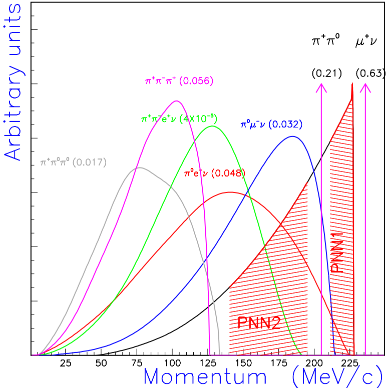
The Secret of Finding Rare Decays - J.Mildenberger (& J.Hart)

E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background with at least two independent cuts.
- It is difficult to simulate background at the 10^{-10} level, so measure background with data by inverting cuts and measuring rejection taking any correlation into account.
- To avoid bias, set cuts using $1/3$ of data, then measure backgrounds with remaining $2/3$ sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- "Blind analysis". Don't examine signal region until all backgrounds verified.

Backgrounds in high momentum (pnn1) region

Mechanisms for the main backgrounds in the high momentum region



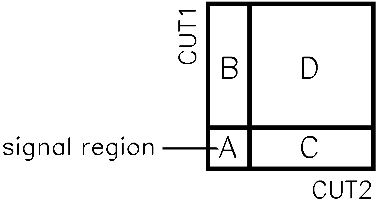
$\mathbf{K^+ \rightarrow \pi^+\pi^0}$ **($\mathbf{K_{\pi 2}}$)**

1. Mismeasurement of π^+ kinematics
2. Undetected photons from $\pi^0 \rightarrow \gamma\gamma$

$\mathbf{K^+ \rightarrow \mu^+\nu}$ **($\mathbf{K_{\mu 2}}$)**

1. Mismeasurement of μ^+ kinematics
2. Misidentification of μ^+ as π^+

Estimation of background rates with data



if CUT1, CUT2 uncorrelated,

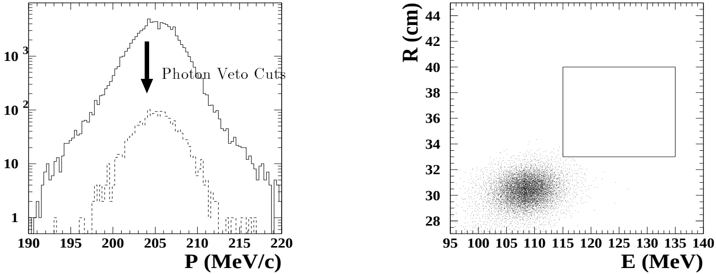
$$A/B = C/D$$

$$A = BC/D$$

- Apply cut2 & invert cut1: Select B events
- Invert cut2: Select C+D events

  & apply cut1: Select C events
- Rejection of cut1 is R = (C+D)/C
- Background estimate = B/(R-1)

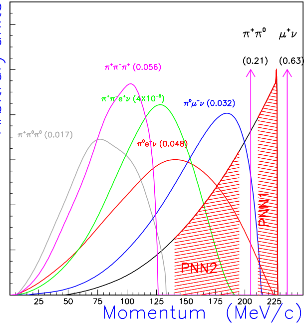
Example: Estimating $K^+ \to \pi^+\pi^0$ pnn1 background with data



Left: Kinematically selected $K^+ \to \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns wide time windows and 0.2 - 3 MeV energy thresholds

Right: Select photons. Phase space cuts in momentum(P), range(R), energy(E)

Backgrounds in the pnn2 region

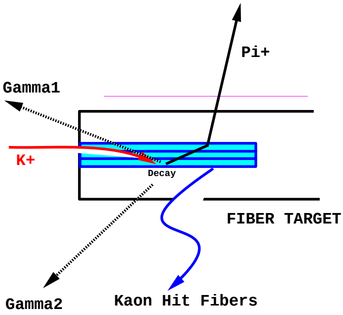


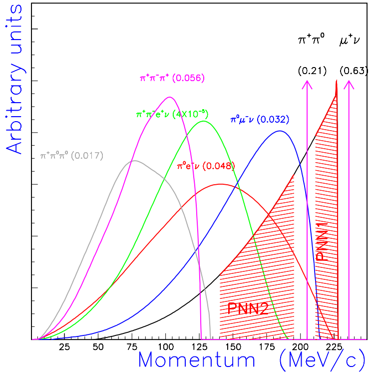
Process	Rate
$\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$	0.8×10^{-10}
$\mathrm{K}^+ \to \pi^+\pi^0$	$2092000000.0 \times 10^{-10}$
$\mathrm{K}^+ \to \pi^+\pi^0\gamma$	$2750000.0 \times 10^{-10}$
$\mathrm{K}^+ \to \pi^+\pi^- e^+\nu$	409000.0×10^{-10}
$\mathrm{K}^+ \to \mu^+\nu$	$6344000000.0 \times 10^{-10}$
$\mathrm{K}^+ \to \mu^+\nu\gamma$	$62000000.0 \times 10^{-10}$
$\mathrm{K}^+ \to \mu^+\pi^0\nu$	$332000000.0 \times 10^{-10}$
CEX	$\sim 46000.0 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.0 \times 10^{-10}$

CEX is mainly $(K^+ n \to K^0 X) \times (K^0 \to K^0_L) \times (K^0_L \to \pi^+\mu^-\nu)$
Determined from $(K^+ n \to K^0 X) \times (K^0 \to K^0_S) \times (K^0_S \to \pi^+\pi^-)$ measurements

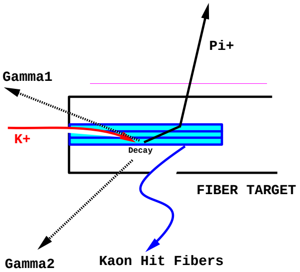
Main pnn2 background: $K^+ \to \pi^+\pi^0$ -scatters

The main background below the $K^+ \to \pi^+\pi^0$ peak is due to $K_{\pi 2}$ decays where the π^+ scatters in the target losing energy simultaneously obscuring the correlation with the π^0 direction.





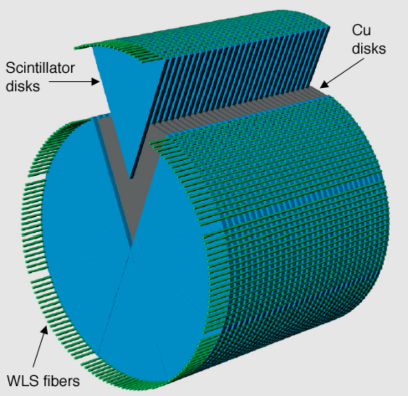
Suppression of $K_{\pi 2}$-scatter background



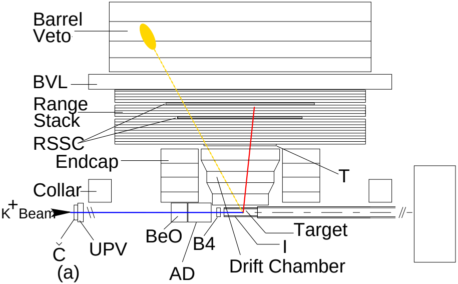
- Photon veto of $\pi^0 \to \gamma\gamma$
  Photon detection in beam region important
- Identification of π^+ scattering in the target
  - kink in the pattern of target fibers
  - π^+ track that does not point back to the K^+ decay point
  - energy deposits inconsistent with an outgoing π^+
  - unexpected energy deposit in the fibers traversed by the K^+

Kinematic suppression not as effective as for pnn1 $K_{\pi 2}$ background.

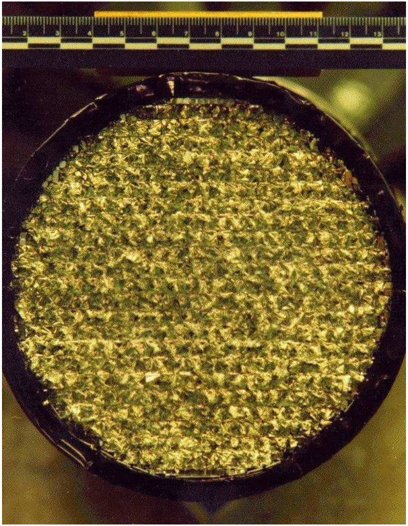
Photon veto in the beam region



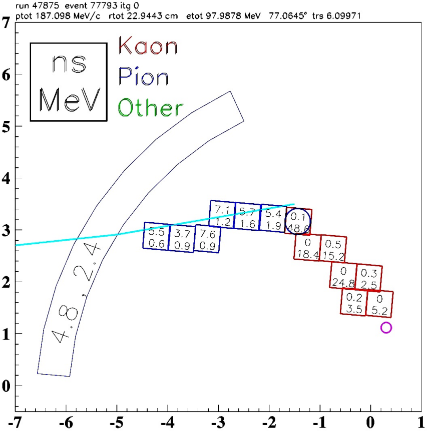
Active Degrader (AD)
14cm diameter, 17cm long,
12 azimuthal segments
6.1 radiation lengths



E949 scintillating fiber target

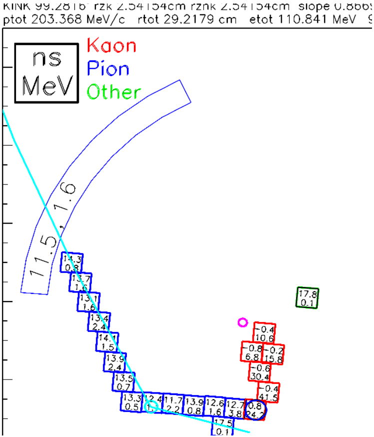


Each fiber is $0.5 \times 0.5 \times 300.0$ cm

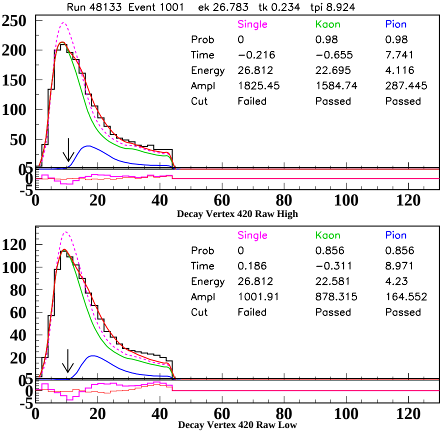


'Typical' pattern in target fibers for $K^+ \to \pi^+\pi^0$ decay.

Identification of π^+ scattering

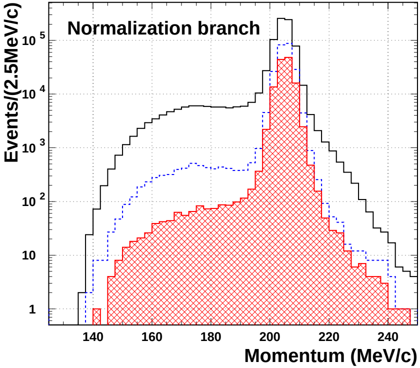


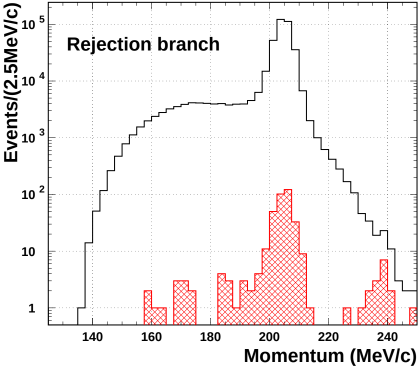
Kink in pattern of target fibers



Excess energy in kaon fibers (“CCDPUL”)

Suppression of $K_{\pi 2}$ scatter background





Black: Photon-tagged sample

Blue: After target cuts (except CCDPUL)

Red: After all target cuts

Black: π^+-scatter-tagged sample

Red: After photon veto cuts

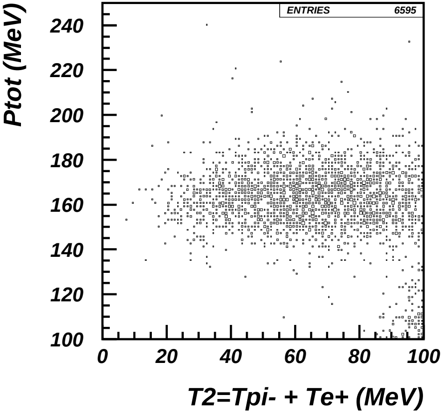
Estimation of $K_{\pi 2}$ scattering background

- $K_{\pi 2}$ scattering background is suppressed by PV and target cuts.
- To estimate PV rejection, multiple π^+ scattering samples are prepared by inverting different combinations of target cuts.
- The "normalization" sample is estimated by inverting the PV cut, but the sample is contaminated with $K_{\pi 2}$ scatters in the range stack (RS) and by $\mathrm{K}^+ \to \pi^+\pi^0\gamma$.

After disentangling the processes:

Process	Background events
$K_{\pi 2}$ TG-scatter	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS-scatter	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2 \gamma}$	$0.076 \pm 0.007 \pm 0.006$

$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4}) background



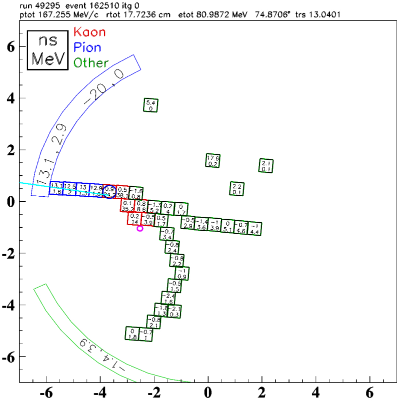
$K^+ \to \pi^+\pi^- e^+\nu$ can be a background if the π^- and e^+ have very little kinetic energy and evade detection.

Figure: π^+ momentum (P_π) *vs.* total kinetic energy of π^- and e^+ from simulated $K^+ \to \pi^+\pi^- e^+\nu$ decays.

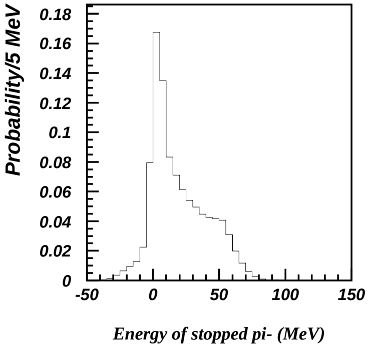
Signal region is $140 < P_\pi < 199$ MeV/c

$K^+ \to \pi^+\pi^-e^+\nu$ background

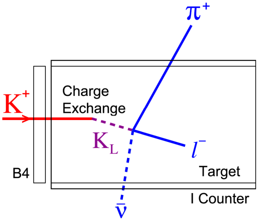
Isolate K_{e4} sample using target pattern recognition, similar to $K_{\pi 2}$ scatter.



Estimate rejection power of target pattern recognition with simulated data supplemented by measured π^- energy deposition spectrum in scintillator.



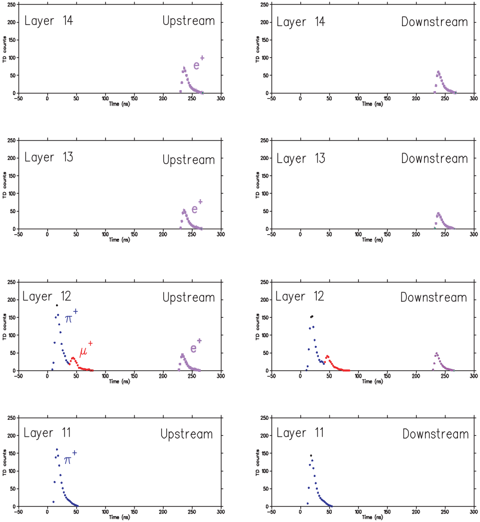
Charge-exchange (CEX) background



CEX background is mainly due to
$(\mathrm{K}^+ n \rightarrow \mathrm{K}^0 X) \times (\mathrm{K}^0 \rightarrow \mathrm{K}^0_\mathrm{L}) \times (\mathrm{K}^0_\mathrm{L} \rightarrow \pi^+ \mu^- \nu)$

Use measured K^0_S events as input to simulation.
The delayed coincidence (DC) cut, $t_\pi - t_\mathrm{K} > 3$ ns, provides suppression because the K^0_L decay must decay in the fiducial region ($\sim$20 cm) of the target.
Additional suppression provided by detection of the lepton.

Muon background



- Previous pnn2 analyses in E787 showed that muon background due to $\mathrm{K}^+ \to \mu^+\nu$ $\mathrm{K}^+ \to \mu^+\nu\gamma$ and $\mathrm{K}^+ \to \mu^+\pi^0\nu$ was expected to be very small (0.016 ± 0.011 events).
- In E949 we relaxed the criteria on identification of $\pi^+ \to \mu^+ \to e^+$ decay chain for a relative gain in acceptance of 10%.

Total background and sensitivity

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total bkgd	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24
	E949 pnn2	**E787 pnn2**
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

The branching ratio that corresponds to one event in the absence of background is the Single-Event Sensitivity (SES).

For the E787+E949 pnn1 analysis, SES $= 0.63 \times 10^{-10}$.

Verification of background estimates

Relax PV and CCDPUL cuts to define 2 distinct regions PV_1 and CCD_1 immediately adjacent to the signal region.

Define a third region PV_2 by further loosening of the PV cut.

Compare the observed ($N_{\rm obs}$) with the expected number ($N_{\rm exp}$) of events in each region.

Region	$N_{\rm exp}$	$N_{\rm obs}$
CCD_1	$0.79^{+0.46}_{-0.51}$	0
PV_1	$9.09^{+1.53}_{-1.32}$	3
PV_2	$32.4^{+12.3}_{-8.1}$	34

The probability to observe ≤ 3 events when $9.09^{+1.53}_{-1.32}$ are expected is 2%.

The probability of the observation in regions CCD_1 and PV_1 given the expectation is 5%; the expectation is [2%,14%] when the uncertainty in $N_{\rm exp}$ is taken into account.

Division of the signal region

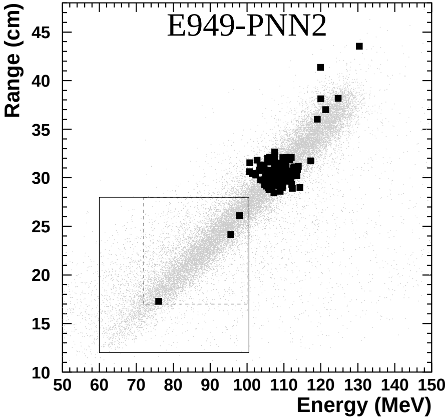
- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of photon veto, delayed coincidence, $\pi \to \mu \to e$ and kinematic cuts to divide the signal region into 9 cells with differing levels of signal acceptance (S_i) and background (B_i).
- Calculate $\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu})$ using S_i/B_i of any cells containing events using the likelihood ratio method.

Examining the signal region

The nine cells

Bkgd	Events	S/B
0.152		0.84
0.038		0.78
0.019		0.66
0.005		0.57
0.243		0.47
0.059		0.45
0.027		0.42
0.007		0.35
0.379		0.20

Examining the signal region

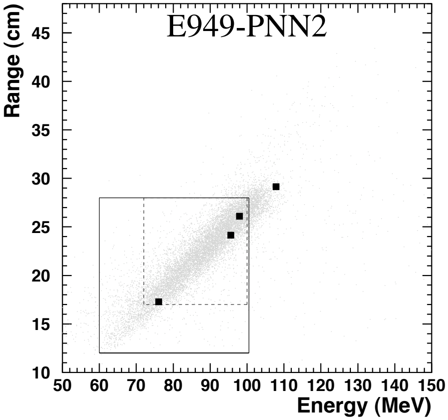


The nine cells

Bkgd	Events	S/B
0.152	0	0.84
0.038	0	0.78
0.019	0	0.66
0.005	0	0.57
0.243	1	0.47
0.059	0	0.45
0.027	1	0.42
0.007	0	0.35
0.379	1	0.20

No momentum cut applied. Solid line represents signal region, dashed line shows tightened kinematic cuts.

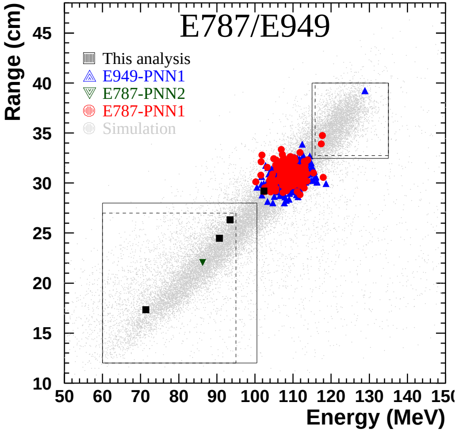
Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ for this analysis



All cuts applied.

- $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$ for the E949 pnn2 analysis
- The probability of all 3 events to be due to background only is 0.037.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$

Measured $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ for E949+E787



E787(dashed) and E949(solid) signal regions shown. All cuts applied.

- $\boldsymbol{\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}}$
- The probability of all 7 events to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$
- Despite the size of the boxes in energy *vs.* range, the pnn1 analyses are 4.2 times more sensitive than the pnn2 analyses
- PRL**101**:191802,2008; arXiv:0903.0030 sub. to PRD

Implications for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

Grossman and Nir (PLB**398** (1997) 163):

$$r_{IS} \frac{\Gamma(K_L \to \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \to \pi^+ \nu\bar{\nu})} = \sin^2\theta$$

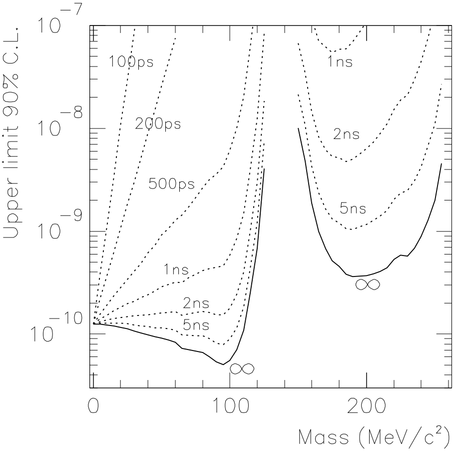
where

$$\begin{aligned} r_{IS} &= 0.954\text{, isospin breaking factor} \\ \theta &= \text{relatve phase between } K-\bar{K} \text{ mixing amplitude and } s \to d\nu\bar{\nu} \\ &\quad\ \text{decay amplitude} \end{aligned}$$

$$\begin{aligned} \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) &< \frac{\tau(K_L)}{\tau(K^+)} \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})/r_{IS} \\ &< 14.6 \times 10^{-10} \quad (90\%\mathrm{CL}) \end{aligned}$$

Current experimental limit: $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 670 \times 10^{-10}$ (E391a, PRL**100**, 201802 (2008).

$K^+ \to \pi^+ X$ interpretation



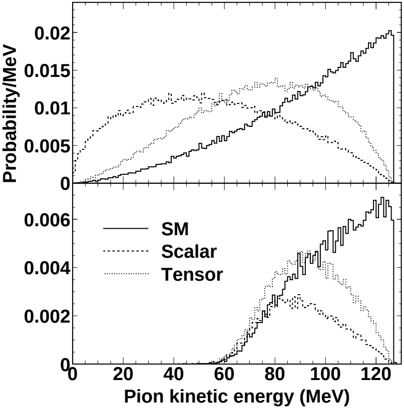
90% CL limits on $K^+ \to \pi^+ X$ where X is a massive non-interacting particle for $\tau(X) \geq 100$ ps, assuming 100% detection efficiency if X decays within the outer radius of the barrel photon veto.

Also: $\mathcal{B}(K^+ \to \pi^+ X) < 5.6 \times 10^{-8}$ (90%CL) for $M(X) = M(\pi^0)$ from limit on $\mathcal{B}(\pi^0 \to \nu\bar{\nu}) < 2.7 \times 10^{-7}$ (E949, PRD**72** 091102 (2005)).

$K^+ \to \pi^+ X$ interpretation

- HyperCP observed 3 events consistent with $\Sigma^+ \to pX$ with $X \to \mu^+\mu^-$ and $M(X) = 214.3 \pm 0.5\ \mathrm{MeV}/c^2$ (PRL**94**, 021801 (2005)).
- $M(X) = 214.3\ \mathrm{MeV}/^2$ corresponds to a recoiling π^+ momentum of $170.1\ \mathrm{MeV}/c$ for the two-body $K^+ \to \pi^+ X$ decay.
- The nearest candidate from E949 & E787 differs by 3.7 standard deviations from $170.1\ \mathrm{MeV}/c$.
- The 90%CL limit from the previous page yields $\mathcal{B}(K^+ \to \pi^+ X)\mathcal{B}(X \to \nu\bar{\nu}) < 3 \times 10^{-9}$.

$K^+ \to \pi^+ XX$ interpretation



Interpretation assuming a scalar or tensor interaction:

$$\mathcal{B}_{\text{scalar}} = (9.9^{+8.5}_{-4.2}) \times 10^{-10}$$
$$\mathcal{B}_{\text{tensor}} = (4.9^{+3.9}_{-2.4}) \times 10^{-10}$$

Figure:
Top is simulated π^+ energy spectra
Bottom are events passing the trigger

What happens next?

- In an ill-considered decision of the Executive Branch of the US Government, E949 was cancelled in 2002 after receiving only 20% of the approved beam time.
- Experiment NA62 (formerly NA48/3) at CERN was approved in 2007 and is in preparation.
- NA62 proposes to observe $\approx$65 $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ per year with a background of $\approx$10 events using a 75 GeV/c beam. The use of kaon decay-in-flight to measure $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ has not been attempted before.
- There is a letter of intent for a stopped kaon decay experiment in Japan using the best parts of E949.
- "A few % measurement of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ appears feasible at Fermilab Project X." - D.Bryman

In 25 years of research with experiments E787 and E949 at the AGS, the search for $\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$ decays went from a limit on the branching ratio of $< 1.4 \times 10^{-7}$ (90%CL) to a measurement of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ that is twice as large as, but still consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.

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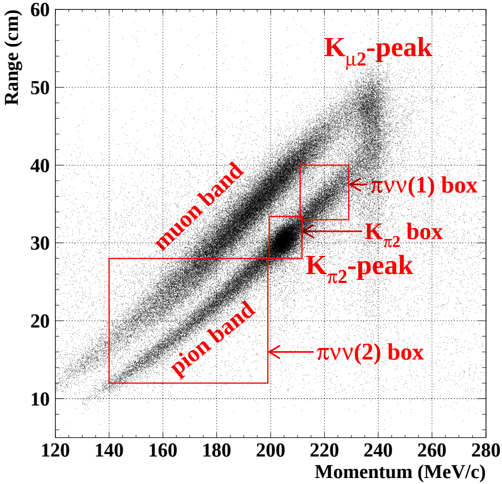
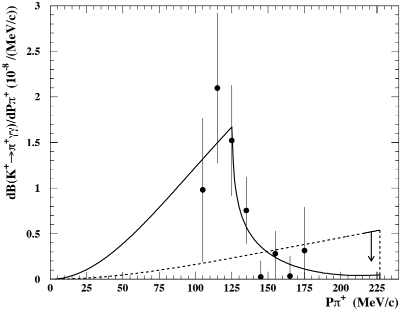
Pion range vs energy for triggered events



$K^+ \to \pi^+\gamma\gamma$ is not a background



Ref: E787, PRL **79**, 4079 (1997).

- Partial branching fraction for $140 < P_\pi < 200\ \mathrm{MeV}/c$ is $\approx 1.1 \times 10^{-7}$.
- Photon veto rejection of $\pi^0 \to \gamma\gamma$ is $> 10^6$.
- Rate of $K^+ \to \pi^+\gamma\gamma$ background is $< 1.1 \times 10^{-13}$ without considerations of π^+ acceptance.

How it began

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: October 17, 1983

TO: T. Kycia, S. Smith

FROM: R.B. Palmer

SUBJECT: E787

I have good news. Proposal 787, "Study of the Decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$", has been approved for the full requested time of 2500 hours. The High Energy Advisory Committee strongly endorsed this proposal, characterizing it as dealing with one of the two most important areas in particle physics today;

E787 and E949 collaborators

117 collaborators, 17 institutes from Canada, China, Japan, Russia and the US.

A.J.S. Smith, A.J. Stevens, A.N. Khotjantsev, A.O. Bazarko, A.P. Ivashkin,A.P. Kozhevnikov, A.S. Turcot, A.V. Artamonov, A. Daviel, A. Konaka, A. Kushnirenko, A. Otomo,A. Sambamurti, B. Bassalleck, B. Bhuyan, **B. Lewis**, B. Viren, C. Ng, C. Ng, C. Witzig, D.A. Bryman, D.E. Jaffe, D.I. Patalakha, D.R. Marlow, D.V. Vavilov, D. Akerib, E.J. Ramberg, E.W. Blackmore, E. Garber, F.C. Shoemaker, G. Azuelos,G. Redlinger, I-H. Chiang, **I.-A. Christidi**, J.-M. Poutissou, J.A. Macdonald, J. Doornbus,J.R. Stone, J.S. Frank, J.S. Haggerty, J.V. Cresswell, J. Hu, **J. Ives**, J. Mildenberger, J. Roy, K.K. Li, K. Mizouchi, K. Omata, K. Shimada, L. Felawka,L.G. Landsberg, L.S. Littenberg, M. Aoki, M. Miyajima, M.A. Selen, M.LeNoble, M.M. Khabibullin, M.V. Diwan, M. Ardebili, M. Burke, M. Convery, M. Ito, M. Kobayashi, M. Kuriki, M. Nomachi, M. Rozon, M.S. Atiya,N.V. Yershov, N. Muramatsu, O.V. Mineev, P.C. Bergbusch, P.D. Meyers, P.S. Cooper, P. Kitching, P. Padley, P. Pile,R.C. Strand, R.Soluk, R. McPherson, R. Poutissou, R. Tschirhart, S.H. Kettell, S.V. Petrenko, S. Adler, S. Chen, S. Daviel, S. Kabe, S. Ng, S. Sugimoto, T.F. Kycia, T.K. Komatsubara, T. Fujiwara, T. Inagaki, T. Nakano, T. Nomura, T. Numao, T. Sasaki, T. Sato, T. Sekiguchi, T. Shimoyama, T. Shinkawa, T. Tsunemi, T. Yoshioka, V.A. Kujala,V.A. Mukhin, V.F. Obraztsov, V.V. Anisimovsky, V. Jain, W.C. Louis,W.Sands, Y. Kishi, Y. Kuno, Y. Tamagawa, Y. Yoshimura, Yi Zhao, Yu.G. Kudenko,and Zhe Wang